Stability and Chaos in Planetary Systems

Gregory Laughlin

One of the major news stories of the year was the detection of multiple planets around a Sun-like star (Upsilon Andromedae). Aside from being a "first" detection, this discovery was very interesting because the arrangement of the three planets in the Upsilon Andromedae system is drastically different from the arrangement of our own system. The two outer Upsilon Andromedae planets are considerably more massive than Jupiter, and they have orbits that are much more eccentric than those of the major planets in our system. However, the radial velocity observations used to make the discovery can determine only a lower limit for the planetary masses. Furthermore, there were several different data sets compiled by competing teams of observers. Two important questions thus remained, both of which were addressed by Ames-based theoretical research:
(a) What is the true mass of the planets? and
(b) Which set of published orbital parameters best represents the true configuration of the system?

Work in FY99 focused extensively on these questions, and examined other aspects of the general problem of planetary orbital stability. By performing over ten billion years worth of numerical integrations covering many different configurations that are compatible with the observed data from the Upsilon Andromedae system, the Ames research effort significantly narrowed the possible orbital parameters of the system. It was proved that in order for the system to survive over the 2–3-billion-year age of the parent star, the orbital planes of the planets are being viewed close to edge-on. This finding indicates that the companion masses are close to their minimal, nominal values, and are hence true planets. It was also shown that the observations of the team from the University of California at Berkeley were likely to be the most accurate. The Ames effort has now been confirmed by several other teams of researchers.

In a related line of research, large-scale numerical experiments have shown how the effects of the close passage of a binary pair of stars can disrupt an otherwise orderly system of planets (see figure 1). This effect is now understood to be important in the dense open clusters that are the birthplace of many stars. In the FY99 research, the simulations were extended to study the ramifications of this process for the history and future of our own solar system. The research showed that the solar system has existed more or less in isolation since its birth. The nearly perfect circular orbit of Neptune indicates that the Sun has never suffered a significant encounter with

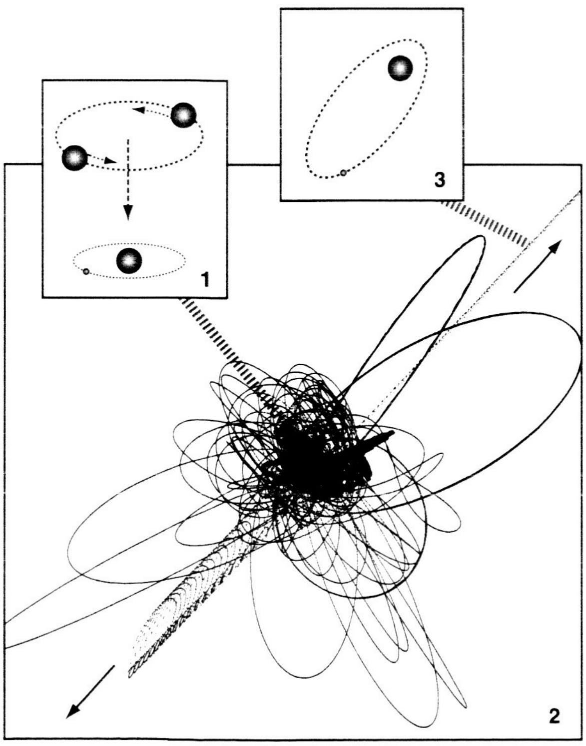

Fig. 1. The computer simulation of figure 1 shows the outcome of a close encounter between a red dwarf binary pair and the Sun-Earth system. The red dwarf pair approaches the Sun from a direction perpendicular to the figure plane. Earth is almost immediately handed off to the smaller star and stays with that star for three long, looping excursions. After slightly more than 1000 years, Earth is recaptured by the Sun, and remains in a solar orbit for the next 6500 years, as the Sun suffers many complicated close encounters with the other stars. After 7500 years, Earth is captured into orbit around the larger red dwarf star, and soon thereafter this star escapes with the Earth in tow. This particular simulation is one of several million performed in order to understand how planetary systems are affected by encounters with the other stars.

another star, suggesting that low-density regions of star formation such as the Taurus Molecular Cloud are the most promising nurseries for planets that eventually develop Earth-like environments. One interesting auxiliary result was the calculation of the odds of Earth being ejected or captured from the solar system by another star prior to the Sun's red giant phase: a scant one part in one hundred thousand!

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Stability of the Upsilon Andromedae Planetary System

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This project studies the dynamical properties of planetary systems that are consistent with the observational data on the three-planet system orbiting the nearby main sequence star Upsilon Andromedae. Some configurations consistent with the data originally announced by the discovery team are found to be stable for at least one billion years, whereas in other configurations planets can be ejected into interstellar space in less than 100,000 years. The typical path to instability involves the outer planet exciting the eccentricity of the orbit of the middle planet to such high values that it ventures close to the inner planet. In some stable systems a secular resonance between the outer two planets prevents close approaches between them by aligning their longitudes of periastron (that is, the orientations of their elliptical orbits). In relatively stable systems, test particles (which can be thought of as representing asteroids or Earth-like planets that are too small to have been detected to date) can survive for long periods of time between the inner and middle planets, as well as exterior to the outer planet. No stable orbits between the middle and outer planets were found.

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Hydrodynamic Simulations of Asteroid Impacts on Venus

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Impact cratering is strongly affected by the presence of an atmosphere. Our solar system offers four relevant targets: Venus, Titan, Earth, and Mars. Our greatest concern is with the Earth, but Venus is the best subject to study, because its atmosphere is about 100 times thicker than the Earth's, and the surface of Venus is randomly peppered with a thousand craters, most of which are apparently little altered since their creation. Thus Venus provides the ideal testbed for theories of atmospheric permeability to stray cosmic bodies—there is both strong atmospheric interaction and enough craters to provide ground truth to calibrate results.

In this study, numerous two-dimensional (2-D) high-resolution hydrodynamical simulations of asteroids striking the atmosphere of Venus were performed. The computations used ZEUS, a grid-based Eulerian hydro-code designed to model the behavior of gases in astrophysical situations. The numerical experiments address a wide range of impact parameters (velocity, size, and incidence angle), but the focus is on 1-, 2-, and 3-kilometer-diameter asteroids, because asteroids of these sizes are responsible for most of the impact craters on Venus. Asteroids in this size range disintegrate, ablate, and decelerate in the atmosphere, yet retain enough impetus to make large craters when they strike the ground. Smaller impactors usually explode in the atmosphere without cratering the surface.

In the simulations, the impactor is broken up by aerodynamic forces generated by the rapid deceleration of the bolide and the shearing flow that develops around it. This results in a complicated and turbulent flow at high Mach number, featuring a broad range of exponentially growing unstable waves. The simulations are sensitive to small differences (both physical and computational) in the initial conditions of the computation. It is found that the shape, resolution, velocity, or other details of the impact can strongly influence which wavelengths grow first, and how quickly. The evolution of each impact is unique, highly chaotic, and sensitively dependent on details of the initial conditions. Atmospheric permeability